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SOME POINTS IN INTRACRANIAL PHYSICS.

IT IS NOT only in discussing the phenomena of mind that the use of metaphysical terms is not merely convenient but imperative. To impute personality to objects, and when abstract notions have been formed to regard these as representing entities,—to endow them with the attributes, passions, powers we ascribe to persons,—are among the earliest efforts of the nascent intelligence. The most highly-trained intellect still finds it convenient to adopt the same plan, and in certain directions finds it difficult to improve on it.

In the development of mind, impression is the first stimulant of consciousness ; appearance—color or form—is the earliest recognition of an impressing agent ; variety and movement are among the first perceptions. Control over certain movements of the body, as in grasping, pushing, pulling, gives an instinctive notion of power ; and the idea of power, once got hold of, dominates our interpretation of every appearance and movement.

It is characteristic of the rational mind that it must seek for causes, and if need be, invent them. It is not content, for example, to describe a feeling, and to say a body *is heavy ;* it desires a reason and says it *has weight.* Wherever work is done the presence of a working agent—of a something that can exert power—is inferred. Such words as "nature," "life," attraction," are constantly on the lips and are regarded as workers. They are spoken of as if endowed with Will, and as acting with an end in view. An anthropomorphic tendency or mode of expression will thus obtrude itself, whether an attempt is made to explain the rolling of a billiard ball, or to fathom the mystery of a first cause.

No term in the language is more wide-reaching in its application—none is more metaphysical—than the word Energy. It refers to the most generalised concept that has yet been given to account for the behavior of matter. It is the central *genus* round which cluster gravity and cohesion, heat, affinity, and other *species.* No appearance—no physical change in the material universe—can be interpreted without the assistance of one or several of its forms. It is the potential of all existence, of all experience, of all force. It is

> "A spirit of activity and life
> That knows no term, cessation, or decay;
> . . . .
> But, active, steadfast, and eternal, still
> Guides the fierce whirlwind, in the tempest roars,
> Cheers in the day, breathes in the balmy groves,
> Strengthens in health and poisons in disease."[1]

If we attempt to define with precision what energy is "in itself" we must simply move in a circle. We are told it is "the power of doing work." But what is power? Another metaphysical word. It is energy in efficient relation to some definite end, and work is evidence of energy spent. In short, energy is an interpretation—an imputed virtue—an article in the creed of scientific faith—a something that satisfies the reason in trying to account for work done.

As a simple fact of existence, however, matter and energy are one and indissoluble. The necessities of language may require their separation in thought, but what we can alone investigate is the behavior of matter. That which gravitates or is heavy is a material body; the atoms that clash together or fly asunder in the play of chemical affinity are solid[2]; it is the commotion of molecules that communicates the feeling of heat; if the ray of light fail to meet and to agitate material particles it remains "darkness visible." We may talk of inertia but cannot conceive of matter being absolutely *inert*. If it has form—if it occupy space—it must have properties. When acted on it will react; when put in motion it may communicate motion.

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[1] Shelly.—The whole of the apostrophe to the "Spirit of Nature" in *Queen Mab* reads like a rhapsody on the doctrine of the conservation of energy.

[2] It would not affect the argument if atoms are "small, soft, flexible, or liquid masses."

Energy doing work becomes force. Force implies motion and has its origin in disturbed equilibrium—in a difference of degree or kind or position.

It is no part of our plan to enlarge on the various kinds of energy or their modes of working. We must, however, glance shortly at some of the characteristics of energy as manifested in organised structures.

Life is a great worker, but it is rather a cluster of energies than by itself a specific form. It is often spoken of as—and, indeed, believed by some to be—an agent which can compel or control motion in opposition to ordinary physical laws. As weight, however, is not something added to bodies, but is implied in the very constitution or concept of matter, so life is simply evidence that several kinds of energy are so co-ordinated that they work in harmony towards one end. The instruments are so small, the motions so subtle, the lines of force so mixed, that it may be impossible to trace all the individual links in the combination and sequence of changes. But science, like theology, has its articles of faith, and one of these is that no break in the continuity of motion can possibly occur.

The solution of the problem lies in the subtle but powerful nature of molecular energy. Capillary attraction, osmosis, chemical affinity, heat, and other physical agencies act each in its own mode. They thus promote the movement and development of protoplasm in the cell, stimulate the growth of tissues, and condition the exercise of function. The force at individual points may be infinitesimally small, but, acting at innumerable centres and through myriads of lines of action, it may be used to so much advantage that, like the impulse from a piston in the hydraulic press, its effects may be great and far reaching. In time these are shown in the formation of large structures or powerful instruments. "As we "look at the roots of a mighty tree, it appears to us as if they had "forced themselves with giant violence into the solid earth. But "it is not so; they were led on gently, cell added to cell, softly as "the dews descended and the loosened earth made way. Once "formed, indeed, they expand with enormous power, but the spongy "condition of the growing radicles utterly forbids the supposition "that they are forced into the earth."[1]

A necessary condition of the development of growing structures is a certain amount of physical restraint. This moulds form and determines the direction of growth. Even in the simplest cell the diffusion of fluids and the movement of granules require the restraint of the cell wall. Without such limiting influence the speck of protoplasm would be speedily resolved into amorphous matter. Under repression the growth or multiplication of cells gives rise to expansive pressure. This, if met by opposing pressure, reacts on the molecules themselves and leads to tension—to an improved adjustment—to storage of energy. The tension becomes a force which, as in the bud, the seed, the egg, can compel firm envelopes to give way, and thus the growth of structure is allowed to proceed in the direction of least resistance.

"Development, then, is due to increase under limit; it is de"termined by resistance. Is it not self-evident? Conceive of an "ovum germinating with all other circumstances unaltered, but "with no external limitations, no membranes, no uterus, nothing "to check expansion in any form. Could anything else result but "a shapeless multitude of cells?"[2] The bearing of all this on intracranial physics will be seen immediately.

The skull may be regarded as a gigantic cell in whose interior the play of various kinds of energy is powerful and unceasing. It is unnecessary here to enlarge upon it as an organ of protection. Its qualities in this respect speak for themselves. We have simply to handle it—to notice that by their configuration and texture its walls are so constructed as to ensure in the most economical manner lightness, strength, and elasticity—in order to recognise its fitness to protect an organ of such delicate structure and important function as the brain.

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[1] Hinton. "On Physical Morphology." *Brit. and For. Med. Chirurg. Rev.* Oct., 1858.

[2] Hinton. *Op. cit.*

But it has another and at least equally important office. It is able to place severe restraint on the forces battling within its cavity, and the thesis I wish now to submit and support in the present paper is that such restraint is necessary to enable the brain to accumulate or concentrate its specific form of energy, and to permit the latter to be liberated with economy and precision.

Assuming in the meantime that an expanding force exists, and that in certain circumstances the brain would become more bulky if the restraint of the cranial wall were withdrawn, it is at once obvious that the greater the expansive force, the greater too must be the reaction on the brain itself. That is to say, *stress*—the tension of combined action and reaction—must be increased. This stress will be equalised through the whole cranial cavity. The brain itself floats on, and is so thoroughly permeated by fluids, that the law of fluid pressure must come into play, and the tension, therefore, will not be greater at one point than at another.

But although stress be equalised, the solid elements of the brain itself may to a limited extent be displaced. They may be so pushed aside by the fluids being augmented or diminished in particular vessels, that from this cause the outcome of the brain's activity may be greatly modified.

Our first step, then, must be to determine the sources of pressure and the factors that may influence its amount and direction.

The main source of intracranial pressure is, of course, the movement of blood in the vessels. The brain is the most vascular of organs, and is fed by four arteries of considerable size. These anastomose freely at the inner base of the skull, and form a circle from which a supply of blood can be readily directed to any part of the brain where for the moment there is a demand for it.

We do not require here to trace in detail the distribution of the various arteries. Suffice it to say they all lose themselves in the *pia mater* in a remarkably fine network of vessels. When they penetrate the brain they are too minute to be traced further with the scalpel. Practically, therefore, the arterial circulation of the whole brain mass is entirely capillary.

Through vessels also of capillary minuteness the venous blood is returned to the veins of the *pia mater*. Having reached this membrane they coalesce, and becoming gradually larger, they cross the surface of the convolutions and empty themselves into the "sinuses" of the *dura mater*. These are channels tunnelled through the firm inelastic tissue of that membrane, and we may afterwards find a reason for such a termination.

The *pia mater*, then, is quite a unique structure. It is simply a complex web of minute arterial and venous vessels. As seen when the *dura mater* is removed it closely invests the whole brain and lies like a fine pad between opposing convolutions.

An interesting mechanical problem here presents itself. How is it that strangulation does not frequently occur in the circulation of the *pia mater?* On the one hand, we have the brain mass, a large, very vascular body whose circulation we may assume is liable, like that of every other organ, to considerable variations; and in immediate contact, but lying completely external to it, is this membrane with a double plexus of vessels, one set feeding and the other draining the nerve-tissues. Now, if an expansive impulse be given to the brain through the arterial vessels, how is it that the membrane is not so compressed against the *dura mater* as to check its circulation altogether? Such an accident would, of course, be serious. It would involve the immediate collapse of the brain-functions.

By keeping this problem in view we will be led to notice some interesting peculiarities in the intracranial circulation and pressures.

In the first place, the arteries enter the skull in a curious fashion. The internal carotid before and after it has left the temporal bone is curved like the letter *s*, and the vertebrals take also a tortuous course on piercing the *dura mater*. Such an arrangement must lessen any direct impetus given to the brain circulation by the action of the heart.

Then the extent to which the arteries at the base of the brain can be over-filled must be extremely limited. The cranial cavity is not only absolutely full, but as it is flushed with fluids moving, as we shall afterwards find, under considerable stress, it may be said to be tensely filled with incompressible material. It is obvious, therefore, that not a drop of blood can enter by the arteries unless an exactly equivalent bulk is at the same moment discharged by the veins. It is also evident that if some sudden impetus threatened to distend the brain beyond physiological limits, its mass would at once react by pressure on the larger arteries themselves and check the flow of blood through them by diminishing their calibre.

A third factor is the relation of the blood in the intracranial veins to the pressure of the atmosphere. As this relationship is one of importance it requires to be treated with some detail.

A glance at the solid structure of the adult cranium may convince any one that the weight of the atmosphere cannot bear directly on the contents of its cavity. Numerous foramina exist, but in the clothed skull every one of these is securely plugged. No fissure can be detected by which the air-pressure can possibly insinuate itself.

Through the blood-vessels, however, that enter or make their exit at the base of the skull, an indirect but most important influence can be brought to bear. Throughout the whole vertebrate kingdom, whatever may be the shape of the skull, or however completely the body of an animal may be encased in unyielding structures, there is always in the neck such an amount of soft textures as will allow the atmospheric pressure to bear on the blood-vessels in that region. As pressure on a fluid is communicated in all directions, then through these vessels the atmosphere may be brought to bear on the whole interior of the cranial cavity. It will be directed therefore, not on the external surface of the vessels, as in most other parts of the body, but on their *internal* surface.

Such a relationship ensures constant fulness of the cranial cavity. Moreover, a little consideration may show that within the latter the mass of blood must be remarkably uniform. The principal contents of the cavity are the brain-substance, the blood, and the cerebro-spinal fluid. No one of these constituents can be altered in bulk unless one or both of the others be altered inversely. So long, therefore, as the brain-substance and the extravascular fluid remain unchanged, the absolute quantity of blood within the intracranial vessels must also remain unchanged, although in its mode of distribution it may be liable to endless variations. Some physiologists suppose that the cerebro-spinal fluid can readily flow to and from the spinal canal and thus affect the mass of blood within the cavity, but we will afterwards find reasons to question the correctness of that opinion.

An obviously important purpose is gained by this relation to the atmospheric pressure. The untoward effect of gravitation on the circulation within the head is completely counteracted. Were the cranial wall as pliable as that of the abdomen, the brain would be liable to endless changes in its amount. Indeed, it would be simply impossible to maintain the erect posture on account of the draining that would immediately take place from the vessels.

Again, in its immediate action on the intracranial circulation, the tendency of the atmospheric pressure will be to favor the movement onwards in the arterial vessels, and to oppose that in the veins. It is to the latter circumstance we have especially to attend at present. The moving blood in the veins must at every moment be subjected to a *backward pressure,* the tendency of which must be to retain the blood within the cavity. It will be communicated through the sinuses of the *dura mater* onward to the smallest veins in the *pia mater,* and from the tension so produced it will prove an important means of preventing the circulation in the membrane from becoming strangulated.

How, then, it may be asked, how can the blood escape from the intracranial sinuses? It can only do so by an equilibrium of pressure being maintained between the surface of the body and the cranial cavity. If the pressure within the latter balances that on the surface the flow of blood will not be interrupted; if it be to the least extent lower, the blood will refuse to circulate. Its exit would be effectually blocked by the atmospheric pressure.

As the moving blood is the agent which directly produces the internal pressure, it becomes important to determine the factors that condition its volume and velocity in the intracranial vessels. Is the action of the heart on the general circulation sufficient to keep up the required pressure, or must some further special assistance be afforded to the capillary circulation? These questions will lead us to discuss the most important of all the problems in intracranial physics.

That the amount of blood determined to individual parts is in proportion to the demand for it is a principle that applies to every tissue and organ in the body. Functional activity increases and rest lessens the demand. In an actively secreting organ, as, for example, the mammary gland, the amount of blood in and transmitted through its vessels in a given time is much greater than when its function is in abeyance.

Considerable difference of opinion exists as to the mechanism by which local distribution is modified. Many eminent physiologists insist that the only source of impulse to the circulation is the action of the heart, and that the vasomotor nerves are to be credited with the power of promoting or limiting local supply. That the action of these nerves may influence the circulation is undoubted, but that they alone are responsible for every local change may be more than questioned. A great deal may be said in favor of the opinion that metabolic activity in the tissue itself has directly to do with local circulation.

In an essay like the present we cannot enlarge on all the side issues that may open up, but as this point is an important one in our discussion I may venture to submit a single "stubborn fact" that bears directly on the question.

Every one who knows anything of anatomy is aware that in the abdomen all the blood returned from the stomach, intestines, etc., has to pass through the liver before it can reach the vena cava, and so be transmitted onwards to the heart. It is first collected into one large vessel—the portal vein. This divides into two branches which enter the liver, one to each lobe. There they subdivide like an artery *until they become minute capillaries;* then gradually uniting and enlarging they form the hepatic vein which empties into the vena cava.

The problem here is: how is this portal circulation kept up? Evidently considerable force must be required to enable such a mass of blood to traverse such an extensive and minute ramification of vessels. Then, unless one of the most fundamental principles in physics be suspended, *that force must react as backward pressure on the blood in the mesenteric veins.* But these are weak, thin-walled vessels that are quite unfit to bear any serious strain.

It has been argued that the suction force of the heart, acting as a *vis a fronte,* is sufficient to enable the portal circulation to be carried on. An obvious fallacy may be detected here. If the suction of the right auricle can affect the movement of blood in the mesenteric veins, it must be because the pliable wall of the abdomen can permit the pressure of the atmosphere to bear on these vessels. But the same pressure will also bear on the whole external surface of the liver, and thus that on the veins is completely neutralised, so far as power to influence the portal circulation is concerned.

What, then, are the forces that keep up that circulation? A survey of all the surroundings precludes the notion of any mechanical force urging the blood onwards from behind. We are therefore driven to the conclusion that, however obscure the mode of operation may be, the unceasing commotion of the tissue molecules must have to do with the movement, as must necessarily be the case with that of fluids in the vegetable kingdom. Just as in brisk combustion, the air, in spite of the repelling influence of intense heat, is drawn with some force from one direction and hurried on in another, so in all the textures where metabolism is going on, the physical interchanges between the fluids within and outside the capillary walls, the chemical affinities, the attractions and repulsions, the inconceivably rapid oscillation of the molecules, all go to constitute a force which draws the blood onwards and *actively* transmits it through the capillaries.

Assuming this view of the capillary circulation to be tenable, we shall find not only that its application to the brain is most important, but that within the skull we may also find convincing evidence of its correctness.

In restricting attention to intracranial *physics,* we have to study the brain as we would any instrument whose energy may at one time be potential and at another kinetic. The essential or dominant factors and the influence of surroundings in modifying the activity of these; the conditions that affect the storage and conservation or intensity of energy, and those that stimulate its liberation or determine the direction of its discharge,—such are some of the points that must be settled before the action of the brain as a physiological organ can be understood.

The dominant factor in intracranial physics is undoubtedly the molecular activity of the grey matter of the brain; and concomitant with that is the circulation of healthy blood. Could some subtly penetrating *x*-rays reveal to us the interior of the working brain, we should find ourselves looking into a veritable maelstrom of commotion. The blood rushing and surging in all directions; myriads of fibrous structures quivering intensely, and the molecules of grey matter oscillating with inconceivable rapidity,—all which, in the absence of demonstration, the imagination to the extent of its faculty must *see*.

So intimate is the relation between the molecular activity and the capillary circulation, that these two agencies must be regarded as practically one factor. In every manifestation of the brain's functions they must work in harmony. In the production of heat or light in ordinary combustion, the carbon and oxygen are *one*, and the specific energy of the brain tissue can no more be exercised without free circulation of blood than fuel can burn without air. The molecular commotion powerfully attracts the blood; the latter conditions the activity of the brain cells and determines the amount and direction of pressure.

If, then, we can specify with a moderate amount of precision some of the conditions that control or modify the movement of the circulating fluid, we may to that extent be able to explain—not the translation of molecular into psychical energy, but—various aspects of cerebral activity, just as the engineer knows how the heat of his furnace may be modified by regulating the supply of air to the fuel.

Taking, then, the brain in full swing of activity,—responding to present, or reviving and weaving into endless combinations former impressions,—charged with an energy which, when liberated, is correlated to the subtlest psychical activity,—the blood will at the same moment flush the capillaries with an actively distending pressure, the brain mass will be at its fullest bulk, and its discharging energy at the strongest. But if energy, potentially strong, be diffused, power is lost. Some physical restraint is essential in order to control the direction of motion and to condition the amount of force. Under repression energy accumulates; it becomes more intense, more concentrated if directed into some special channel; more ready to cause explosion if an easy pathway is not opened. In the brain, therefore, outward pressure is speedily met by counter-pressure, partly passive in the unyielding cranial wall, partly active in the energetic movement of fluids on its external surface.

We thus become impressed by the circumstance that the functions of the brain must be exercised under considerable stress. Individual forces seem to be acting in direct antagonism to one another. Currents of fluids are rushing with great velocity and pressing in opposite directions. Then remembering that all this takes place in a space whose capacity is rigidly fixed, we find there must be great tension within the whole cranial cavity.

In physics we have endless illustrations of the behavior of energy under stress. It strives to reveal itself, and all nature gives evidence of its success. The super-heated steam, surging in vain against the walls of the boiler, spends its force on the piston and puts powerful levers in motion. The illustration which perhaps affords the best analogy to the conditions of nervous energy is the storage and discharge of electricity in the accumulator. The molecular structure of certain substances with suitable surroundings can be so charged with that form of energy, that notwithstanding violent commotion in the material particles, it can be confined like water in a cistern and may thence be tapped with marvellous precision.

One of the immediate physical results of uniform tension through the cranial cavity will be that a tendency to vibration will be favored. The brain-substance itself is pulpy, and no more able to vibrate than a bit of soft clay, but under the tension of energetic molecular motion and active capillary circulation the whole contents of the cavity will be subjected to the laws of fluid pressure, and a thrill at one point may make its influence felt through the whole space. The brain may thus be likened to a musical instrument with its chords all taut and ready to respond with a clear tone to the slightest sympathetic touch.

As is well known, Dr. Hartley traced all the functions of the brain, whether receptive or responsive, to vibrations. The speculations of that author have been considered obsolete and are now seldom referred to, but, although his physiology is vitiated by the circumstance that he places the whole energising power in the "white medullary substance," and that he does not enter into the physical conditions of vibrations, some of his "observations" may still be worth recalling.

> "External objects impressed upon the senses occasion, first, in the nerves on which they are impressed, and then in the brain, vibrations of the small, and, as one may say, infinitesimal medullary particles.
>
> "These vibrations are movements backwards and forwards of the small particles; of the same kind with the oscillations of pendulums, and the tremblings of the particles of sounding bodies. They must be conceived to be exceedingly short and small, so as not to have the least efficacy to disturb or move the whole bodies of the nerves or brain. . . .
>
> "The vibrations are excited, propagated, and kept up partly in the ether, i. e., in a very subtle and elastic fluid, and partly by the uniformity, continuity, softness, and active powers of the medullary substance of the brain, spinal marrow, and nerves. . . .
>
> "One may conjecture, indeed, that the rays of light excite vibrations in the small particles of the optic nerve by a direct and immediate action, for it seems probable from the alternate fits of easy transmission and reflexion, that the rays of light are themselves agitated by very subtle vibrations, and consequently that they must communicate these directly and immediately to the particles of the optic nerves. . . .
>
> "As soon as the vibrations enter the brain they begin to be propagated freely every way over the whole medullary substance; being diminished in strength in proportion to the quantity of matter agitated."[1]

Hartley's conjectures as to the transmission of impressions are probably quite correct, and the intracranial tension will help to sustain the vibrations through the brain-substance. Having traced these to the sensory centre, and found the molecular energies of the latter in such play as to impress the consciousness, the physicist stops. Unlike Hartley, he does not venture to affirm that sensations *are* vibrations.

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[1] *Observations on Man; His Frame, His Duty, and His Expectations.* By David Hartley, M. D. (1749.)

Turning to the motor centres and still restricting attention mainly to physical conditions, we shall find that something more than molecular and capillary activity is required for the successful discharge of their energy. If the principle that action and reaction are equal and contrary is of universal application, it must apply not only to the brain as a whole, but also to every energising centre, whether it subserves sensory, motor, or higher functions. In discharging its energy each motor centre has, of course, it own molecular activity greatly raised. This involves more excited circulation and consequently greater outward pressure. Now, if this is not met by a sufficiently stable reaction-pressure, the result will be failure of function. If the surrounding structures, instead of resisting, yield by allowing themselves to be pushed aside, tension in the centre will be lessened, energy will be diffused, and the resulting force will bear with less effect.

A one-pound weight can be lifted with ease ; in lifting fifty-six pounds considerable effort is required. The arm muscles involved are in each case the same ; the physical action of the brain must be very materially modified.

The nerve-centres in the brain for the muscles of the arm are very limited in extent, and are formed of material that, if exposed, might be bruised to pulp by the pressure of a finger. How is it that their energy can be so concentrated that powerful effects can be produced?

In lifting a heavy weight with the hand, provision must be made for preserving the equilibrium of the body itself, and the means required for this purpose also serve for giving the necessary support to the energising centre. The assistance of a large number of other muscles is required, and as one after another is called into play, tension in a series of corresponding centres is also increased. The stress so occasioned being equalised through the whole cranial cavity, the means of concentrating energy in a limited area are afforded. A fulcrum is found for the moving power. Thus the energetic use of a very few muscles may involve the active co-operation of the whole cerebral apparatus. Straining tension on the one hand and steady support on the other are essential. However strenuously the Will may attempt to operate, it will fail in the presence of a flaccid brain. We may as well expect the piston of an engine to be efficiently raised when there is a rent in the boiler, or look for a brilliant stream of electric light by simply rubbing a bit of amber.[1]

If our arguments as to the existence and degree of intracranial tension be tenable,—if pressures occur simultaneously from various directions, and if the stress so occasioned is necessary for efficient discharge of function,—two corollaries may be drawn. In the first place, something more than the *vis a tergo* from the action of the heart will be required to maintain the cerebral circulation. The influence of vasomotor nerves here is *nil.* The most careful research has failed to discover their presence, and yet changes in local distribution through the brain must be of constant occurrence. The blood will move through the vessels, not passively, but with an actively distending force resulting from the direct influence of molecular changes. These powerfully *attract* the blood and urge it onwards through the vessels.

In the second place, the opinion of physiologists as to the behavior of the cerebro-spinal fluid must be modified. There can be no question as to the immense importance of this fluid. Wherever one part of the brain so overlaps another that the surfaces are not in perfectly close apposition, there we have it present. Its use is to give such an amount of steady hydrostatic pressure as will maintain an equal strain through the cranial cavity, and thus to prevent jolt or jar to the delicate nerve-structures. But if it can fluctuate between the cranial and spinal cavities with the ease many writers assert, it would become a source of positive danger instead of being an important agent in conserving the brain's energy. If any sudden or strong strain be required, it would be apt to move away when its passive but steady support may be most essential, and the conditions of successful discharge of energy would be therefore weakened. Of course, if a strain be kept up for a length of time, the fluid may be absorbed or it may be increased according as the pressure is from the brain itself or is within the veins, but as between the cranial and spinal cavities it must in ordinary circumstances be practically a stable quantity.

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[1] An interesting illustration from pathology may be given to show how an important influence, purely physical in its nature, may be exerted by one centre on another. In the disease called "locomotor ataxy" the power of so co-ordinating the muscles as to control the *direction* of movement is greatly impaired. There is no paralysis, but the muscles fail to work in harmony. The spinal cord is considered to be the principal seat of disease, but tone appears to be lowered in all the higher nerve centres. A patient so affected may stand with tolerable steadiness *so long as he keeps his eyes open.* But let him shut his eyes and he not only becomes unsteady, but, if not supported, *he will fall heavily to the ground.* Thus the centre for vision when active—keeping a certain hold on its circulation and therefore on cerebral pressure—affords such favorable mechanical conditions for the play of some motor centres, that if in certain circumstances its influence be withdrawn no effort of the Will can prevent complete collapse.

It would lead us far beyond the limits of a paper like the present to discuss fully the various modes in which by their mutual reactions on one another the active brain and its correlated circulation may throw light on psychical operations. I shall simply touch on a single point where the physical element is still an important factor.

The mass of blood in the intracranial vessels being practically a fixed quantity, no alteration can occur in one set of vessels or in one region of the brain without an inverse change taking place in some other quarter.

If we take the brain at any moment when its functions are quiescent but not suspended, a certain equilibrium in its circulation must be present. This equilibrium will be disturbed at once if a stimulus—sensory, volitional, or ideational—call any special centre into brisk activity. The blood will be determined toward that point in fuller volume. This focussing of the circulation will react on the centre itself and condition or increase its energising powers. Its function will be exercised with greater efficiency. But as the absolute mass of blood that can be drawn on is limited, less of that fluid can at the same moment be allowed to other parts, and therefore the functional capacity of the latter must be lowered.

For example, if the centre for vision be impressed by an extensive landscape, and the consciousness is engrossed in discriminating its varied features in detail,—hill and valley, forest and meadow, river and lake,—the centres for ideation must be deprived of such share in the circulation as is required for successful energising, and the reasoning faculty will be therefore in comparative abeyance. On the other hand, if the solution of some problem requiring close consecutive thinking is being successfully carried out, the balance will be away from the sensory centres and impressions on these will be blunted. The features of the landscape now become blurred or they are not at all noticed.

The existence of some such principle—the possibility of an infinitesimally graduated equilibrium in the circulation occurring in response to local molecular requirements—must underlie and condition the various phases of attention; and if of attention, then of volition and all the other mental activities. But we cannot further enlarge on this aspect of our subject. Enough has been said to show that it is greatly owing to the fact that the brain is "cribbed, cabined, confined" within a rigidly limited space that its functions can be exercised with smoothness and efficiency. We may now inquire, shortly, whether the elementary physical principles we have been making use of may not also be of service in discussing the conditions that are required to ensure rest to the fatigued brain.

In trying to frame a theory as to the causation of sleep, what should we look for?

In the first place, some mechanism must be discovered which, if put in action, can enforce physiological rest to the brain. The mechanism must be gradual in its operation, but ultimately so effective that that organ will for the time be unable to respond to ordinary impressions, or to afford the conditions of coherent thought. In the second place, it must be powerful enough to keep the brain's functions in abeyance sufficiently long to allow such repair or readjustment of the molecular structures to take place that a reserve of nerve energy may be stored up. Lastly, it must be such that if a stronger stimulus—sensory, emotional, or rational—shall require it, the period of sleep may be postponed, or the soundest sleep may be broken, and a state of alert wakefulness at once restored.

A moment's consideration may convince one that metabolic change alone, or that along with simply diminished circulation, will not fulfil these indications. We can understand, indeed, that the molecular energy of the brain may be so exhausted that functional capacity for the time being will be lost; or we can suppose the circulation to be so far reduced that the brain may be unfit to subserve any mental function. But if either or both these conditions contributed all that would be necessary to induce sleep, serious drawbacks would be associated with their working. The period when sleep would supervene would not depend on the convenience of the individual, but would occur whenever a certain amount of katabolic change had been brought about. Moreover, some local centre or centres becoming exhausted before others, co-ordination among them would be lost. A state of dreaming—of incoherent thought and diminished voluntary control—would be constantly occurring. In short, mental unity would be destroyed.

An additional factor, then, is still lacking, but before referring to it, an important fact in connexion with the exercise of brain functions requires to be noticed.

If the brain be exposed by injury of the skull, consciousness can be at once suspended by a certain amount of pressure being applied to its surface. This fact has long been known. In some cases alternations of waking and sleep could be brought about at the will of the operator. The reason may possibly be analogous to the effect produced by a rude touch on a vibrating bell or wire,—vibration is checked and the tone vanishes. Also, some change in the capillary circulation is likely to have to do with it. The question, then, comes to be: have we any means—physiological in origin but mechanical in operation—available for the purpose of producing compression of the brain? If so, we may find a clue to the conditions that are effective in sleep.

Now, in the venous circulation of the *pia mater* we have such a means, and its mode of operation may be traced with tolerable precision.

We have already seen that these vessels are being constantly acted on by two opposing forces. There is, in the first place, the pressure of the brain mass on their *external* surface tending to obliterate them ; and, secondly, there is the backward pressure occasioned by the weight of the atmosphere bearing on their *internal* surface, and tending to dilate them. Here then we have an interesting but simple problem in the composition of forces. Is a constant equilibrium preserved between them, or is there an ebb and flow in one or in both?

The pressure of the atmosphere may be regarded as practically a constant quantity. It of course varies, but any change will affect arterial and venous vessels alike. In ordinary circumstances, therefore, its variations cannot appreciably influence the intracranial circulation.[1]

The expansive pressure of the brain, however, varies considerably. After a certain amount of functional activity the molecular commotion naturally tends to become languid, and, as the direct result of this, the capillary circulation is less energetic. The blood pressure within the vessels must now bear outwards with less force, and the expansive tendency of the brain as a whole will therefore be weakened.

When this condition has been induced, and if the terms of the problem have been correctly stated,—if no essential factor has been overlooked,—it becomes very evident what will happen. The atmospheric pressure will now bear with greater effect within the venous vessels. It has not become stronger, but the opposing force is weaker. The vessels will become distended by the movement of blood being retarded. Until a stable equilibrium has been again reached, *more blood will enter the veins than is being expelled from the skull.*

This conclusion may be argued in another way. It is the united testimony of all those who have investigated the subject experimentally, that during sleep the brain mass *contracts.* The following is Dr. Hammond's statement as to what he noticed while observing the brain of a dog through an opening in the skull. "While this "state (of sleep) was coming on I watched the brain very atten-"tively. Its volume slowly decreased; many of its small blood-"vessels became invisible, and finally it was so contracted that its "surface, pale and apparently deprived of blood, *was far below the "level of the cranial wall.*"[1]

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[1] One reason why, in addition to the less stimulating effect of the oxygen of the air, the power of exertion is so crippled in high altitudes, may be that the greatly diminished pressure on the venous system of vessels within the skull allows the blood to escape too readily from the cavity. There is not sufficient backward pressure to serve as a fulcrum against the energising, and therefore outwardly distending, brain mass.

But if the brain tends to contract it must give rise to a *suction* effort. Is there any structure or fluid on which this can be exerted with success? It is simply impossible that a vacuum can be left. The absolute fulness of the cranial cavity must still be maintained. Evidently, the cranial wall cannot respond; it is too rigid. Nor can the fluid in the spinal canal respond, it is completely removed from the direct influence of the atmospheric pressure. The only structure that can respond is the moving blood in the veins of the *pia mater,* and it can only do so by its flow being retarded, and of course, by the vessels becoming distended.

This altered balance in the circulation does not affect the absolute mass of blood within the skull; it only affects its mode of distribution. It will still happen that for every drop that enters the cavity, an equal quantity must at the same moment be dislodged into the jugular veins.

At this stage, then, we find the following physical conditions: first, the capillary circulation of the brain diminished; second, the veins of the *pia mater* distended; and third, the mass of brain substance contracted or compressed; can we assign to these conditions any physiological significance?

Unless some serious fallacy in our argument has been fallen into, it may with confidence be submitted that in the sequence and combination of these conditions, we have sufficient material to enable us to frame a theory as to the induction and continuance of sleep. No one of them by itself can be called the *cause* of sleep.

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[1] *On Wakefulness.* By William A. Hammond, M. D.

Compression of the brain is only the last stage of a sequence, and it may be considered permissive as much as enforced. The molecular commotions are still at every step and stage the dominant factor. A slight increase of stimulus may undo the whole inhibitory process, and with molecular activity restored we have wakefulness and intelligence. The compression, however, is required in ordinary circumstances to secure a sufficiently long rest. A certain amount of vibratory energy is still maintained. Those forms of metabolic activity which are purely nutritive and reparative must be kept up. These lead to recuperation—to improved adjustment—to storage of energy—to restored function.

We can now appreciate the reason why the venous blood from the *pia mater* is emptied into channels with firm inelastic walls, instead of being carried on to an outlet in the skull in vessels of the ordinary kind. The pressure from the veins is not of a passive nature. It is derived from the *moving* fluid within them and is therefore active. The volume of their contained blood will determine the amount of pressure they exert. Then the numerous contributories to one vein would soon so increase its bulk that the pressure from it would be simply paralysing in its effect. The brain structures would fail to react sufficiently against it. The venous sinus is therefore so constructed that its capacity is scarcely, if at all, affected by pressure either from within or from without its walls.

I do not pretend to have exhausted all the modes in which the bearing of elementary physical principles on intracranial activities may be considered. I hope I have said enough, however, to show that their study deserves more attention than is usually given. In coming to close quarters with the problems of psychology more progress is likely to be made by taking a comprehensive survey of general relationships and mechanical adjustments than from exhaustive microscopic and chemical research. However interesting the facts may be in themselves, it cannot be said that much light has been thrown on the brain's mode of energising by having ascertained the size and shape and disposition of its cells and fibres. A knowledge of the molecular structure of a lever may enable one to judge of its fitness for a particular purpose, but it does not reveal to us the laws of leverage. The relations of the moving power to the resistance to be overcome and to the point of resistance that must be stable are to be learned in other ways. So with the brain, the wider the survey we can take of the physical conditions and relations that affect its working, the more impressed will we be with the number whose influence must be focussed in every act of successful cerebration, and therefore in every manifestation of correlated mental activity. However subtle the latter may be,—however independent of all physical trammels the meditating, reasoning-comprehending soul may seem to itself to be,—the brain is still the indispensable energising agent, and as such it cannot escape the tyranny of mechanical limitations and adjustments, nor of the laws to which all motions are subservient.

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